

# Reinstating the M31 X-ray system RX J0042.3+4115 as a black hole X-ray binary, and compelling evidence for an extended corona

R. Barnard, and M. R. Garcia

*Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge MA 02138*  
and

S. S. Murray

*Johns Hopkins University, Baltimore, Maryland*

## ABSTRACT

The M31 X-ray source RX J0042.3+4115 was originally identified as a black hole binary because it displayed characteristic low state variability at conspicuously high luminosities; unfortunately, this variability was later found to be artificial. However, analysis of 84 Chandra ACIS observations, an HST ACS/WFC observation, and a 60 ks XMM-Newton observation has supplied new evidence that RX J0042.3+4115 is indeed a black hole binary. The brightest optical star within  $3\sigma$  of the position of RX J0042.3+4115 had a F435W ( $\sim B$ ) magnitude of  $25.4 \pm 0.2$ ;  $M_B > -0.4$ , hence we find a low mass donor likely. RX J0042.3+4115 was persistently bright over  $\sim 12$  years. Spectral fits revealed characteristic black hole binary states: a low/hard state at  $2.08 \pm 0.08 \times 10^{38} \text{ erg s}^{-1}$ , and a steep power law state at  $2.41 \pm 0.05 \times 10^{38} \text{ erg s}^{-1}$  (0.3–10 keV). The high luminosity low state suggests a  $\sim 20 M_\odot$  primary; this is high, but within the range of known stellar black hole masses. The inner disk temperature during the steep power law state is  $2.24 \pm 0.15 \text{ keV}$ , high but strikingly similar to that of GRS 1915+105, the only known Galactic black hole binary with a low mass donor to be persistently bright. Therefore RX J0042.3+4115 may be an analog for GRS 1915+105; however, other mechanisms may account for its behavior. We find compelling evidence for an extended corona during the steep power law state, because compact corona models where the seed photons for Comptonization are tied to the inner disc temperature are rejected.

*Subject headings:* x-rays: general — x-rays: binaries — black hole physics

## 1. Introduction

The M31 X-ray source RX J0042.3+4115, named following Supper et al. (1997), was originally identified as a black hole X-ray binary by Barnard et al. (2003), after analyzing 4 XMM-Newton observations from 2000–2002. It apparently exhibited power density spectra (PDS) that were well described by a broken power law, with spectral index  $\alpha$  changing from  $\sim 0$  to  $\sim 1$  at some break frequency; such a PDS is consistent with the low/hard states observed in all

X-ray binaries, whether the accretor is a neutron star or black hole (see e.g. van der Klis 1994; Wijnands & van der Klis 1999). Neutron star X-ray binaries tend to exhibit such behaviour at luminosities around  $10^{36}$ – $10^{37} \text{ erg s}^{-1}$ , yet RX J0042.3+4115 exhibited this variability at 0.3–10 keV luminosities of  $\sim 1$ – $3 \times 10^{38} \text{ erg s}^{-1}$ . Barnard et al. (2003) concluded that RX J0042.3+4115 contained a black hole.

However, it was later discovered that these PDS and those reported by other groups were contaminated by artifacts caused by the XMM-

Newton data reduction software (Barnard et al. 2007). The problem arose because all XMM-Newton lightcurves start at the arrival time of the first photon by default; hence, source and background lightcurves, and lightcurves from the three EPIC detectors—MOS1, MOS2, and pn—are asynchronous by default. Combining these lightcurves (e.g. combining instruments, or background subtraction) often resulted in PDS with artificial broken power law shapes.

Therefore we make no use of the PDS and instead rely on our well established method of using low state emission spectra (power law emission with photon index 1.4–1.7 and little to no thermal emission, McClintock & Remillard 2006) at conspicuously high luminosities to identify black hole candidates (Barnard et al. 2008; Barnard & Kolb 2009; Barnard et al. 2011). We present the most detailed justification of our selection criteria in Barnard et al. (2011).

In this paper we present our analysis of 84 Chandra ACIS observations of RX J0042.3+4115 over  $\sim 12$  years, and our serendipitous HST observation, along with our re-analysis of the 60 ks 2002 XMM-Newton observation. We use the HST data to place RX J0042.3+4115 in M31, and argue for a low mass donor. We use long-term and short-term variability, and also emission spectra, to reinstate RX J0042.3+4115 as a black hole candidate. We discuss the observations and data analysis in the next section, followed by our results in Section 3, and a discussion in Section 4.

## 2. Observations and analysis

We analyzed 84 Chandra ACIS observations of the central region of M31, spaced over  $\sim 12$  years, using CIAO version 4.3. For each observation we extracted 0.3–7.0 keV source and background spectra from circular regions with  $10''$  radius; the background region was close to the source region, and source free. Corresponding response matrices and ancillary response files were also made. We obtained 0.3–10 keV luminosities from each observation using XSPEC version 12.6.0.

Observations with  $>200$  net source counts were freely fitted with absorbed power law models; spectra were grouped to give at least 20 counts per bin. For observations with  $<200$  net source counts we assumed an absorbed power law model

with  $N_{\text{H}} = 1.0 \times 10^{21}$  atom  $\text{cm}^{-2}$  and  $\Gamma = 1.5$ , and found the 0.3–10 keV luminosity equivalent to 1 count  $\text{s}^{-1}$ , then multiplied this conversion factor by the intensity; we chose this model because it approximates the best fit to our deepest Chandra observation of RX J0042.3+4115 in its low state. Luminosity uncertainties for freely fitted spectra are estimated by XSPEC by calculating a range of fluxes obtained by varying the emission parameters; the uncertainties for the faint spectra are derived directly from intensity uncertainties.

Additionally, we analyzed the 60 ks 2002 January XMM-Newton observation of M31 (Rev 381) with SAS version 10.0.0. We extracted 0.3–10 keV EPIC-pn lightcurves and spectra from circular source and background regions with  $15''$  radius. The background region was on the same CCD as the source region, and at a similar off-axis angle. The spectra were grouped to ensure a minimum of 50 counts per bin.

RX J0042.3+4115 was serendipitously observed in one of our HST ACS/WFC observations of M31 transients. Observation j9ud17010 was made on 2009 August 25, with the F435W filter for 4360 s. We registered a combined Chandra 0.3–7.0 keV image and the HST image to the same B band image provided by the Local Group Galaxy Survey (Massey et al. 2006) using the IRAF task CCMAP; we used X-ray bright globular clusters to register the Chandra image, and bright, unsaturated stars to register the HST image. We determined the best X-ray position of RX J0042.3+4115 with the IRAF task IMCENTROID. We used the IRAF package DAOPHOTII to perform photometry on the stars within  $3\sigma$  of the position of RX J0042.3+4115.

## 3. Results

### 3.1. The search for an optical counterpart

The centroid of the X-ray emission from RX J0042.3+4115 was located at RA = 00:42:22.954, Dec = 41:15:35.23, with  $1\sigma$  uncertainties of  $0.009''$  in RA and  $0.007''$  in Dec. Combining this with the r.m.s. uncertainties in registration yields X-ray positional uncertainties of  $0.09''$  in RA and  $0.19''$  in Dec.

Figure 1 shows a detail our HST image, superposed with an ellipse representing the  $3\sigma$  uncertainties in the position of RX J0042.3+4115.

There are several stars within the ellipse, the brightest of which has a Vega B magnitude of  $25.4 \pm 0.2$ . We therefore constrain the B band magnitude to  $\gtrsim 24.8$ . We see no evidence for a background galaxy; the region is relatively uncrowded, as it is  $\sim 4'$  from the M31 bulge, and the detection limit is  $B < 28$ . There is no evidence for a counterpart in the 2MASS All Sky Catalog (Skrutskie et al. 2006), hence RX J0042.3+4115 cannot be associated with a late type star in our Galaxy. We conclude that it is located in M31.

The distance modulus for M31  $\sim 24.5$ , and we can estimate  $A_B$  by using the empirical relations  $A_V \sim N_H / 1.8 \times 10^{21} \text{ atom cm}^{-2}$  (Predehl & Schmitt 1995), and  $E(B-V) \sim A_V / 3$ . The column density varied significantly between observations, hence the variable component was probably internal to the system. Since the donor is unlikely to suffer this extra absorption, we assume  $N_H = 1.0 \times 10^{21} \text{ atom cm}^{-2}$  (see below), and  $A_B = 0.7$ . Therefore  $M_B \gtrsim -0.4$ .

The known counterparts of high mass X-ray binaries (HMXBs) in the SMC have apparent V magnitudes in the range  $13 \lesssim m_V \lesssim 18$ , and  $B - V$  in the range  $-0.32 \leq B - V \leq 0.06$  (see e.g. Coe et al. 2005; Antoniou et al. 2009). For a distance of  $\sim 60 \text{ kpc}$ , this equates to  $-6 \lesssim M_B \lesssim -1$ , all brighter than our threshold of  $M_B \gtrsim -0.4$ .

The three known BH HMXBs are Cygnus X-1, LMC X-1 and LMC X-3. Cygnus X-1 has a counterpart with  $M_V = -6.5$  (Walborn 1972) and  $B - V = 0.8$  (Hiltner 1956). The counterpart to LMC X-1 has magnitude  $V = 14.60 \pm 0.02$  and  $B - V = 0.17 \pm 0.08$  (Orosz et al. 2009); hence  $M_B \sim -4.2$  for a distance of  $50 \text{ kpc}$ . LMC X-3 has a  $B \sim 17$  counterpart (see e.g. Brocksopp et al. 2001), and  $M_B \sim -1.5$ ; this is  $\sim 8\sigma$  brighter than the brightest star within the ellipse.

RX J0042.3+4115 is therefore most likely to be a low mass X-ray binary (LMXB).

### 3.2. Time variability

We present the  $\sim 12$  year 0.3–10 keV luminosity lightcurve of RX J0042.3+4115 created from the 84 ACIS observations in Fig. 2; circles mark luminosities from freely-fitted bright spectra, while crosses represent faint spectra where we assume  $N_H = 1.0 \times 10^{21} \text{ atom cm}^{-2}$ , and  $\Gamma = 1.5$ . Uncertainties are quoted at a  $1\sigma$  level. The lightcurve

is extremely variable, with the luminosity varying over  $\sim 0.5\text{--}3 \times 10^{38} \text{ erg s}^{-1}$ . We note that the spectral fits to all bright observations are consistent with a constant  $\Gamma$ , although  $N_H$  varied by a factor  $\sim 5$ ; the faint observations may be up to 40% times brighter.

RX J0042.3+4115 appears to be persistently bright. By contrast, most Galactic black hole LMXBs are transient. One exception is GRS 1915+105; a 7 year RXTE/ASM lightcurve of GRS 1915+105 showed it to be persistently bright (McClintock & Remillard 2006). Another possible exception is GRS 1758-258; it is thought to be a Galactic LMXB, but its true nature is not confirmed due to the high degree of absorption (see e.g. Muñoz-Arjonilla et al. 2010, and references within).

We also examined the short term variability of RX J0042.3+4115 during the long XMM-Newton observation. We present the 0.3–10 keV EPIC-pn intensity lightcurve for RX J0042.3+4115 in Fig. 3, along with the background lightcurve in grey for comparison. The intensity varies by a factor 2 ( $4\sigma$  deviation) in  $<10 \text{ ks}$ , hence the emission is dominated by a single source. The probability of RX J0042.3+4115 consisting of multiple bright variable sources is very low, especially since it is not associated with any globular cluster.

### 3.3. Spectral analysis

#### 3.3.1. Chandra observation OBSID1575

The longest ACIS observation of RX J0042.3+4115 was OBSID1575, an ACIS-S observation with a  $\sim 40 \text{ ks}$  exposure time; the net source spectrum contained 7690 photons. An on-axis source with this intensity would be in danger of pile-up; however, RX J0042.3+4115 was  $\sim 4'$  off-axis, and the photons were spread over a large number of pixels ( $>100$ ). Each incoming photon is assessed by its impact on a  $3 \times 3$  array of ACIS pixels; “good” photons are detected in only 2 of the 9 pixels, while cosmic rays etc. are detected in 3 or more (Davis 2001). We therefore estimated the probability of pile up from the brightest pair of pixels; this pair accumulated 807 photons over  $\sim 38 \text{ ks}$ , or one photon every  $\sim 14$  frames. Hence, we conclude that pile up is unlikely to have been significant.

The 0.3–7.0 keV spectrum of RX J0042.3+4115 during observation OBSID1575 is well described

by an absorbed power law, with line-of-sight absorption  $N_{\text{H}} = 1.0 \pm 0.2 \times 10^{21} \text{ atom cm}^{-1}$  and photon index  $\Gamma = 1.46 \pm 0.05$ ;  $\chi^2/\text{dof} = 211/204$ . The 0.3–10 keV luminosity was  $2.08 \pm 0.08 \times 10^{38} \text{ erg s}^{-1}$ . Uncertainties are quoted at a 90% confidence level. Figure 4 shows the unfolded 0.3–7.0 keV spectrum multiplied by the channel energy, assuming the best fit absorbed power law model.

When a disk blackbody component was added to the power law emission, XSPEC set the inner disk temperature to  $8.2 \times 10^{-4} \text{ keV}$ , with  $N_{\text{H}} = 1.0 \pm 0.2 \times 10^{21} \text{ atom cm}^{-1}$ , and  $\Gamma = 1.46 \pm 0.05$ ;  $\chi^2/\text{d.o.f} = 211/202$ . Hence there is no trace of a disk component in the 0.3–7.0 keV spectrum. We therefore conclude that RX J0042.3+4115 was in its low state during this observation; since the theoretical upper luminosity limit for low states in neutron star X-ray binaries is  $\sim 3 \times 10^{37} \text{ erg s}^{-1}$ , RX J0042.3+4115 is a likely black hole candidate (see e.g. Barnard et al. 2011, and references within).

### 3.3.2. XMM-Newton Rev 381

The 0.3–10 keV EPIC-pn spectrum of RX J0042.3+4115 contained 21765 net source photons over  $\sim 55$  ks of live time, or  $\sim 0.4 \text{ count s}^{-1}$ . The detector was operated in Full Frame mode, with 73.4 ms frame time; hence, pile-up was negligible.

An absorbed power law model failed to fit the spectrum; the best fit model yielded  $N_{\text{H}} \sim 1.5 \times 10^{21} \text{ atom cm}^{-2}$  and  $\Gamma \sim 1.7$ , but  $\chi^2/\text{dof} = 412/348$ , with a null hypothesis probability of 0.011.

We also tried an absorbed disk blackbody model, since this is characteristic of the thermal high state identified in black hole binaries (e.g. McClintock & Remillard 2006). The best fit column density was a factor  $\sim 3$  lower than the Galactic line-of-sight density ( $6.7 \times 10^{20} \text{ atom cm}^{-2}$ ), hence we fixed it to this value. This resulted in an inner disk temperature of 1.5 keV, but  $\chi^2/\text{dof} = 765/349$  and a null hypothesis probability of  $3 \times 10^{-33}$ . Hence, RX J0042.3+4115 was clearly not in the thermal high state.

A disk blackbody + power law model described the spectrum very well, with  $N_{\text{H}} = 2.4 \pm 0.06 \times 10^{21} \text{ atom cm}^{-2}$ , inner disk temperature  $kT_{\text{in}} = 2.24 \pm 0.15 \text{ keV}$ ,  $\Gamma = 3.0 \pm 0.6$ , and  $\chi^2/\text{dof} = 343/346$ . Figure 5 shows the un-

folded spectrum multiplied by channel energy, assuming the best fit model. The 0.3–10 keV luminosity was  $2.41 \pm 0.05 \times 10^{38} \text{ erg s}^{-1}$ , with the power law component contributing  $\sim 45\%$ . Such a spectrum is consistent with the steep power law black hole binary state described by McClintock & Remillard (2006). The disc temperature is rather higher than usual, but consistent with the Galactic black hole binary system GRS 1915+105; McClintock & Remillard (2006) provide a sample spectral fit for GRS 1915+105 with  $kT_{\text{in}} = 2.19 \pm 0.04 \text{ keV}$  and  $\Gamma = 3.46 \pm 0.02$ .

Some authors have claimed that such a model is unphysical, because the power law component exceeds the thermal component at low energies; they argue that the observed soft excess is an artifact of the two component model (see e.g. Roberts et al. 2005; Gonçalves & Soria 2006). These arguments assume a compact corona that can only access photons from the inner disk. However, there is substantial evidence for extended coronae in X-ray binaries at high luminosities; the ingress times of photo-electric absorption dips in high inclination binaries indicate coronae with diameters of  $\sim 20,000$ – $700,000 \text{ km}$  (Church 2001; Church & Bałucińska-Church 2004), while broadened emission lines in Chandra observations of Cygnus X-2 suggest a hot, dense corona of up to  $\sim 10^5 \text{ km}$  (Schulz et al. 2009). Such coronae would have access to the soft photons from the outer regions of the disc as well as the hot photons from the inner disc.

Indeed, fitting the spectrum with a more physically motivated model (DISKBB + COMPTT in XSPEC) yielded the same values for  $N_{\text{H}}$  and  $kT_{\text{in}}$  as the disk blackbody + power law model, along with a seed photon temperature of  $\sim 0.02 \text{ keV}$ , an electron temperature of  $\sim 40 \text{ keV}$  and an optical depth  $\sim 0.2$ ;  $\chi^2/\text{dof} = 343/344$ ; the electron temperature was unconstrained, and good fits were obtained for electron temperatures of 100 keV and 300 keV also, typical for the BH low state. Tying the seed photon temperature to  $kT_{\text{in}}$  resulted in an unacceptable fit:  $\chi^2/\text{dof} \geq 453/346$  (null hypothesis probability  $< 1 \times 10^{-4}$ ). These results are entirely consistent with an extended, optically thin corona, and reject a compact corona that only sees the innermost region of the disk.

#### 4. Discussion

Although the original evidence for RX J0042.3+4115 being a black hole binary was contaminated by artifacts in the XMM-Newton data reduction software, we now have new evidence that it is indeed a black hole candidate.

Our constraint on the B magnitude ( $M_B > 24.8$  at the  $3\sigma$  level) is extremely useful for interpreting the system. RX J0042.3+4115 is clearly not located in our galaxy, and there is no background galaxy with  $B \lesssim 28$ ; hence we locate RX J0042.3+4115 in M31. The  $3\sigma$  upper limit to  $M_B = -0.4$ , meaning that a low mass donor is most likely.

We have observed two distinct spectral states from this system, consistent with the low/hard and steep power law black hole states. The low state was observed at a 0.3–10 keV luminosity of  $2.08 \pm 0.08 \times 10^{38} \text{ erg s}^{-1}$ , while the steep power law state was observed at  $2.41 \pm 0.05 \times 10^{31} \text{ erg s}^{-1}$ . Since transitions from the low state occur at  $L \lesssim 0.1 L_{\text{Edd}}$  in the 0.01–1000 keV band for NS systems (Gladstone et al. 2007), and in the 15–50 keV band for neutron star and black hole systems (Tang et al. 2011), we suggest that RX J0042.3+4115 was near  $0.1 L_{\text{Edd}}$  during Chandra observation 1575. Such a system would require a  $\sim 20 M_\odot$  black hole; this is larger than for any Galactic black hole binary, but smaller than the dynamically confirmed black hole in IC10 X-1, which has a best mass estimate of  $32.7 \pm 2.6 M_\odot$ , and a lower limit of  $23.1 \pm 2.1 M_\odot$  (Silverman & Filippenko 2008).

RX J0042.3+4115 has been persistently bright for the last  $\sim 12$  years; this is quite unlike the transient behaviour of most Galactic black hole LMXBs. The only known persistently bright black hole LMXB is GRS 1915+105, which has remained bright since its discovery in 1992 (McClintock et al. 2006). The X-ray behavior of GRS 1915+105 is unmatched by any Galactic black hole binary, and may be explained by the primary spinning in the same direction as the accretion disk at extreme speeds ( $>98\%$  of the maximum McClintock et al. 2006). Such prograde spinning allows the last stable orbit to be significantly closer to the black hole than for a non-spinning black hole, resulting in a higher disk luminosity and also a higher  $kT_{\text{in}}$  (Zhang et al.

1997).

The inner disk temperature for RX J0042.3+4115 in the steep power law state ( $2.24 \pm 0.15 \text{ keV}$ ) was remarkably similar to that of GRS 1915+105 ( $2.19 \pm 0.04 \text{ keV}$  for an example spectrum, McClintock & Remillard 2006). Hence, the persistent X-ray emission from RX J0042.3+4115 may also be due to extreme prograde spin. However, we note that 5 out of the 6 black hole candidates that we have associated with M31 globular clusters are persistent also (Barnard et al. 2008; Barnard & Kolb 2009; Barnard et al. 2011); such systems are consistent with theoretical predictions for tidal capture of main sequence donor stars (Kalogera et al. 2004), or ultra-compact systems with degenerate donors (Ivanova et al. 2010). Therefore, several mechanisms can promote persistently bright black hole binaries.

Finally we note that compact corona models where the seed photon energy is tied to the inner disk temperature were all rejected by the XMM-Newton Rev 381 spectrum of RX J0042.3+4115. However, free fitting of the seed photon energy yielded a good fit at 0.02 keV; this result gives strong support for an extended corona in the intermediate/steep power law state, which is able to access the cooler photons in the outer disc. We drew the same conclusions for the confirmed black hole + Wolf-Rayet binary IC10 X-1 (Barnard 2010).

#### Acknowledgments

We thank the anonymous referee for thoughtful comments that significantly improved this paper. We also thank Z. Li for providing the merged ACIS image. This research has made use of data obtained from the Chandra data archive, and software provided by the Chandra X-ray Center (CXC). This work also used an observation from XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA member states and the US (NASA). Furthermore, this work has used data from the Hubble Legacy Archive. R.B. is funded by Chandra grant GO9-0100X and HST grant GO-11013. M.R.G. and S.S.M. are both partially supported by NASA grant NAS8-03060.

*Facilities:* CXO (ACIS) HST (ACS) XMM-Newton (EPIC-pn).

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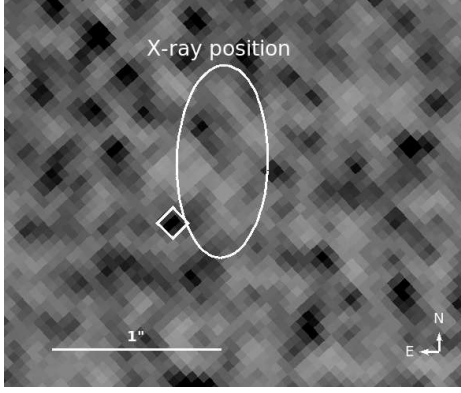


Fig. 1.— A detail of the HST ACS/WFC image from observation j9ud17010; the exposure time was 4360 s, and the F435W ( $\sim$ B band) filter was used. The white ellipse represents the  $3\sigma$  uncertainty in the position of RX J0042.3+4115. North is up, east is left. The brightest star consistent with the ellipse is indicated by a diamond; it has a Vega B band magnitude of  $25.4 \pm 0.2$ .

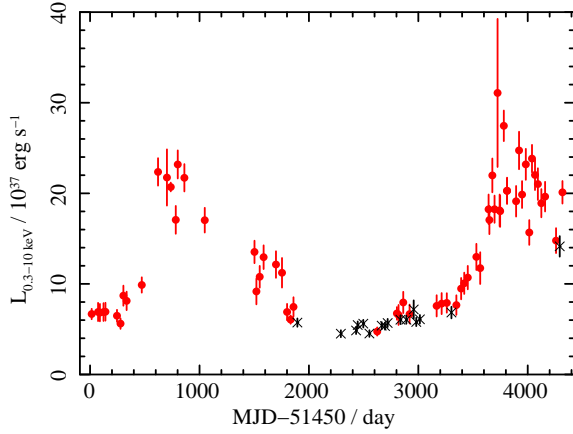


Fig. 2.— Long-term, calibrated luminosity lightcurve of RX J0042.3+4115 from  $\sim 12$  years of Chandra ACIS observations. The luminosity varied by a factor  $\sim 6$ . Circles represent luminosities from freely fitted spectra, while crosses represent “faint” spectra. Uncertainties are quoted at the  $1\sigma$  level.

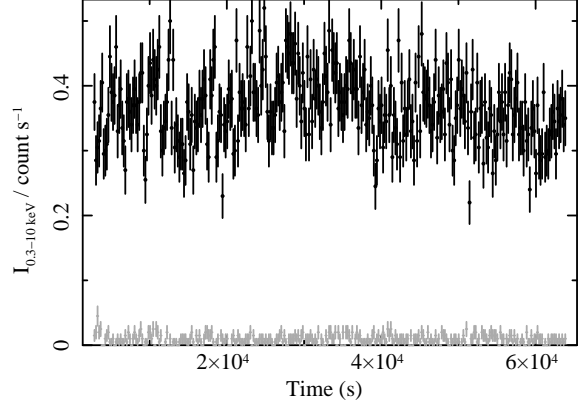


Fig. 3.— EPIC-pn 0.3–10 keV lightcurve of RX J0042.3+4115 from the 60 ks Rev 381 observation. The background lightcurve is shown in grey for comparison. We see that RX J0042.3+4115 is significantly variable over short time-scales, varying by a factor 2 in  $< 10$  ks.

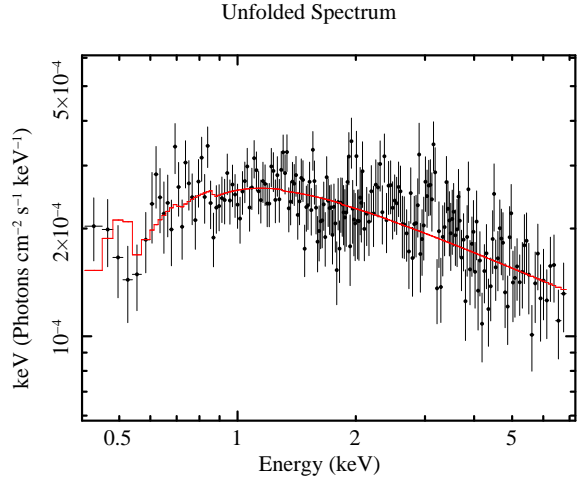


Fig. 4.— Unfolded spectrum for ACIS observation 1575, multiplied by energy. It is well described by an absorbed power law with  $N_H = 1.0 \pm 0.2 \times 10^{21}$  atom  $\text{cm}^{-2}$ , and  $\Gamma = 1.46 \pm 0.06$ ;  $\chi^2/\text{dof} = 211/204$ . Such a spectrum is characteristic of the low/hard state seen in neutron star and black hole binaries (McClintock & Remillard 2006).

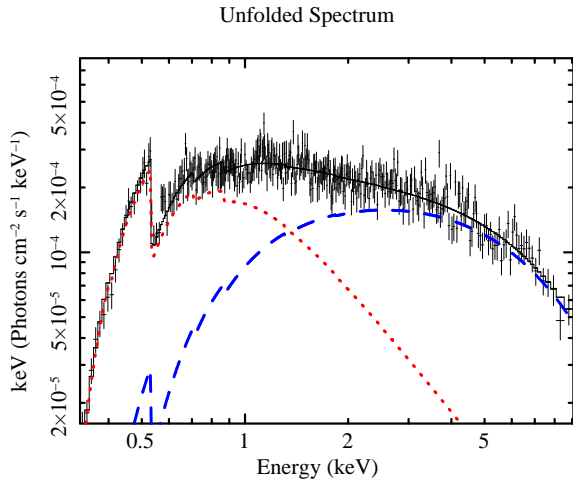


Fig. 5.— Unfolded spectrum for the 60 ks XMM-Newton observation Rev 381, multiplied by energy. It is well described by a disk blackbody (dashed) + power law (dotted) emission model, suffering line-of-sight absorption.  $N_{\text{H}} = 2.4 \pm 0.6 \times 10^{21} \text{ atom cm}^{-2}$ ,  $kT_{\text{in}} = 2.24 \pm 0.15 \text{ keV}$ , and  $\Gamma = 3.0 \pm 0.6$ ;  $\chi^2/\text{dof} = 343/346$ . Such a spectrum is characteristic of the steep power law state seen in black hole binaries; the temperature is higher than is generally observed for Galactic black hole binaries, but is consistent with GRS 1915+105 (McClintock & Remillard 2006).